APPLICATION OF ENGINEERING FUNDAMENTALS TO EVALUATION OF DUST COLLECTION DEVICES

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One consequence of the high degree of mechanization of modern coal mining techniques is the production of a large amount of coal dust during the process of bringing the coal from seam to surface. Wide-spread use of the continuous mining machine has contributed substantially to coal production figures, but it has also added to the level of coal dust in the air the miner breathes. Dust control techniques for the area around a continuous mining machine are relatively ineffective up to the present, compared to other dust sources in the mining operation.

One of the possible approaches to this problem is to collect the dust at or near the mining face as it is generated. In late 1969 a one year contract was awarded by the U.S. Bureau of Mines to Garrett Research and Development Company to evaluate those types of commercially available dust collection equipment which might be applicable to this purpose.

In retrospect, the work done in performance of this contract provides a clear example of how engineering fundamentals can be applied toward solving problems of industrial significance. Two such problems which arose during the planning of this work were: first, what is respirable dust, and what efficiency would be required of a collection device in the underground mining environment? -- and second, how could we evaluate representative dust collection devices with only a small amount of time-consuming experimental work, and yet obtain results which would be general enough to apply to devices and operating conditions other than those specifically investigated?

Details of this work such as experimental procedures are discussed in earlier papers (1,2) and in the final contract report (3).

RESPIRABLE DUST

Mine dust control regulations currently in effect are based on allowable loadings of respirable dust in the mine atmosphere. From the legal point of view, respirable dust is that part of the total dust which is collected by certain portable sampling devices after the dust passes through sections of those devices intended to simulate the dust-collecting abilities of the nose and throat. In order to specify the performance required of a dust collector in a coal mine entry, it is necessary to do the following:

1. Define the size distribution of the "total dust," i.e., the dust generated by a continuous mining machine at a working face.

2. Compute the size distribution of respirable dust, i.e., the part of the total dust which would pass the pre-classifier ("nose and throat") of a portable sampler.

3. From an estimate of the respirable dust loading in a mine, determine the respirable dust collection efficiency required to reduce the respirable dust loading to a legal level.

Three sources of data on dust from continuous coal mining operations were used: the U.S. Bureau of Mines (4), publications of E.J. Baier (5), and mine samples taken as part of this work. With the assumption that the total dust size distribution was logarithmic-normal, and after resolving some inconsistencies in the available data, it was concluded that a conservative (i.e. small) estimate of the size distribution of the total dust near the working face is a mass mean diameter of 15 microns with a standard deviation of 3.0. The size distribution of the respirable dust fraction was then calculated by combining the total dust size distribution with collection efficiency data for the respirable dust sampler. The resulting size distribution for the respirable dust fraction based on the AEC sampler collection efficiency data is a mass mean diameter of 2.55 microns with a standard deviation of 1.7.

The loading of respirable dust in the mine atmosphere near a continuous mining machine has been estimated at 5 to 10 mg/m^3, based on the AEC personal sampler. The current maximum allowable respirable dust loading to which a miner may be exposed is 2 mg/m^3. However, this limit is based on measurement with the MRE portable sampler which, because its pre-classifier operates on a different principle, measures dust loadings differently from the AEC sampler (6,7). An approximate relationship between the dust loadings measured by the two samplers is

$$MRE = 1.63 \text{ AEC} + 0.67 \qquad 1)$$

Thus, the legal limit of 2 mg/m^3 (MRE) corresponds to an AEC-measured loading of 0.81 mg/m^3. Accepting a conservative (high) 10 mg/m^3 estimate for the loading of respirable dust from the continuous miner, the collection efficiency of a device must be

$$\frac{10 - 0.8}{10} = 92\%$$

on respirable dust in order to achieve compliance.

The problem now is, given experimental measurements on the performance characteristics of a dust collection device, how can this information be related to that collector's efficiency on respirable dust? Obviously it is impractical to attempt to use sample dust with the exact size distribution of respirable dust for performance tests on collection equipment. The overall efficiencies measured, therefore, will pertain to the size distribution of the sample dust, rather than respirable dust. The solution is to use a testing procedure which determines the collection efficiency as a function of particle size, so that the primary result of each test is a <u>penetration function</u> $P(D_p)$, the fraction of particles of diameter D_p which penetrates (is not collected by) the collector. (Efficiency and penetration are related by $E \equiv 1 - P$.)

The size distribution of a dust is defined by $f(D_p)$, where $f(D_p)dD_p$ is the mass fraction of particles having a diameter in the range D_p to $D_p + dD_p$, and

$$\int_0^\infty f(D_p)dD_p \equiv 1 \qquad 2)$$

The gross penetration for any dust through any collection device can be calculated from

$$P = \int_0^\infty P(D_p)f(D_p)dD_p \qquad 3)$$

where $P(D_p)$ is the penetration function of the collection device and $f(D_p)$ is the size distribution frequency of the dust. Thus, if the penetration function can be measured or calculated for a given collection device, it is possible to calculate the gross penetration of any dust of known size distribution.

A numerical integration computer program was written to perform the integration of Equation 3, so that the effect of any penetration function and size distribution on gross penetration could rapidly be calculated.

It was implied earlier that the size distribution and loading of respirable dust in a coal mine are not well known. This means Equation 3 is a particularly valuable tool, because it separates the effects of the dust size distribution and the penetration function of the collection device. Hence, experimental results expressed in the form of a penetration function for a given device have complete generality and are applicable to any dust whose size distribution is known.

DUST COLLECTION MECHANISMS

Several basic mechanisms can be used for particle collection, including gravity, inertia, diffusion, electrostatic attraction, fabric filtration, radiation, magnetism, and agglomeration. Most of these are either impractical or dangerous for use in the control of coal dust underground (3). Only inertia and fabric filtration appear to be technically feasible mechanisms in an underground mine, and because of space limitations, inertia is the more promising. Accordingly, this work was limited to investigation of collection devices operating by one or more inertial mechanisms.

Since the intent of the program was not simply to test several commercial dust collection devices but rather to determine what collection mechanisms could best be applied to the problem of coal mine dust, the strategy adopted was to select or develop a mathematical model for each potentially applicable mechanism and to test collection devices which used these mechanisms in order to confirm or disprove the models. With the ultimate goal of evaluating each inertial mechanism for application to coal dust, the immediate goal of the modelling and testing program was to determine for each inertial mechanism the penetration function $P(D_p)$ under various operating conditions. Once this was done, the penetration function could be applied using the technique described in the previous section.

Cyclone

In a cyclone separator, rotary motion of the entire gas stream throws dust particles to the outer wall under the influence of centrifugal force. The particles then fall through the bottom of the cyclone or are otherwise removed. The cyclone separator tested in this work was a multiple cyclone collector consisting of a bank of 46 small cylindrical cyclones in parallel. The dusty air inlet flow was parallel to the axis of the cyclone, and a tangential motion was imparted to the air by fixed vanes set at an angle to the axis. Each cyclone had a hub occupying the central part of its volume. This device was modelled by adapting equations given in Strauss (8) for more conventional cyclones. In this model it was assumed that if a particle reaches the outer wall at any time before leaving the cyclone with the gas, it is collected. No consideration was given to re-entrainment by the gas. The resulting penetration function is given by

$$P(D_p) = 1 - \frac{1 - \sqrt{1-(D_p/C)^2}}{1 - \left(D_{hub}/D_{shell}\right)^2} \qquad 4)$$

where C is a constant characteristic of the cyclone geometry and the air and dust properties. The observed dust penetration through the multiple cyclone as a function of particle size is shown in Figure 1. The curve was calculated from Equation 4. (The value of C in Equation 4 was calculated from the model, not fitted empirically.) The observed gross penetration of the test dust was 76%, and the gross penetration calculated using Equation 4 with Equation 3 was 79%.

It was concluded that within the precision of the experimental techniques used, the penetration function of Equation 4 is an adequate representation of the penetration function of the multiple cyclone which was tested. Equation 4 was then used again as the penetration function in Equation 3 to predict that the gross penetration of respirable dust through this device would be 53% at the test conditions. This is to be compared with the estimated 92% efficiency (8% gross penetration) required to achieve a legal respirable dust loading.

Curved Passages

Many dust collectors use essentially the same principle as the cyclone separator, but the gas is caused to turn by curved passages of some sort. This type of collector includes those with louvers, deflectors, or corrugated passages, and packed beds. In these devices, dust particles are spun out against solid or liquid surfaces by centrifugal force as the gas stream flows through a multitude of curved paths.

A simple packed bed scrubber was fabricated in-house to represent this collection mechanism. For a packed bed, the penetration function can be expressed (9) as

$$P(D_p) = \exp\left[-C \frac{Z}{D_t} K\right] \qquad 5)$$

MULTIPLE CYCLONE
PENETRATION AS FUNCTION OF PARTICLE DIAMETER

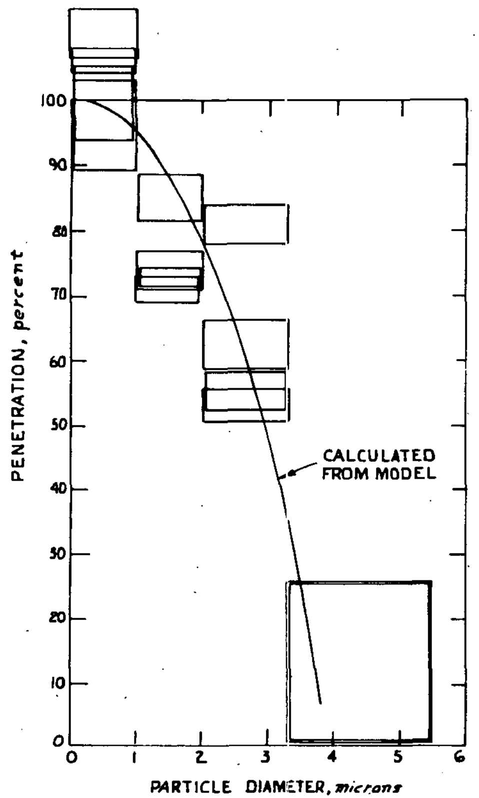

FIGURE 1

PACKED BED SCRUBBER
PENETRATION AS FUNCTION OF PARTICLE DIAMETER

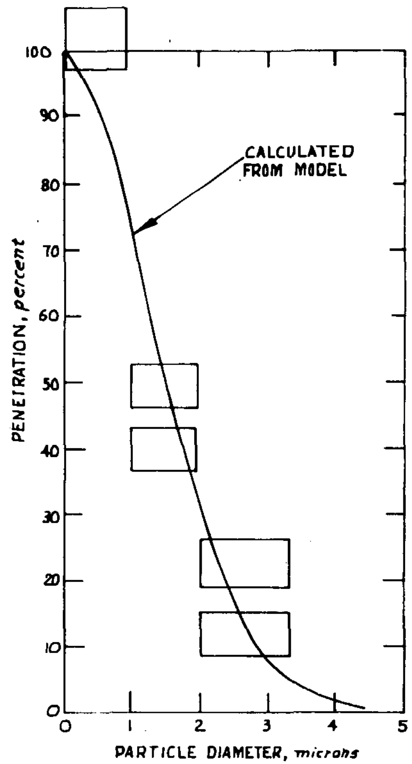

FIGURE 2

where K is the inertial impaction parameter, $U\rho D_p^2/9\mu D_t$, and C is an empirical constant (9) which depends on the packing geometry. The test results for the packed bed scrubber are shown in Figure 2. The curve was calculated from Equation 5 using a value of C = 12 for 1-1/2 inch Pall rings. The observed gross penetration of the test dust was 39%, and the gross penetration calculated using Equation 5 with Equation 3 was 41%.

Impaction Targets

Cylindrical objects such as rods, wires, and fibers are used in a large number of collection devices. As the gas stream flows around the target, the inertia of the dust particle tends to make it impact on the target instead of passing around it. The factors influencing the collection efficiency of such a device are the gas velocity relative to the impaction target, the size of the target, the gas viscosity, the number of targets the gas stream must pass, and the particle density and size. All of these effects except the number of targets are included in the inertial impaction parameter K. An empirical penetration function based on past experimental results for impaction on cylinders and on spheres is

$$P(D_p) = 1 - \left(\frac{K}{K+0.7}\right)^2 \qquad 6)$$

(Impaction on spheres is one of the mechanisms involved in a venturi scrubber, discussed below.)

A wetted screen device was tested which employed the impaction target mechanism. An accordion pleated screen constituted the impaction targets, and the screen was continuously wetted to keep the collected particles from blinding it. The screen was followed by a horizontal cyclone functioning as an entrainment separator. The test results are shown in Figure 3. The higher of the two penetration curves was calculated from Equation 6 directly. However, since the total area of the screen wires was about twice the cross sectional area of the scrubber, it was hypothesized that the scrubber might comprise two impaction stages. The penetration

WETTED SCREEN SCRUBBER
PENETRATION AS FUNCTION OF PARTICLE DIAMETER

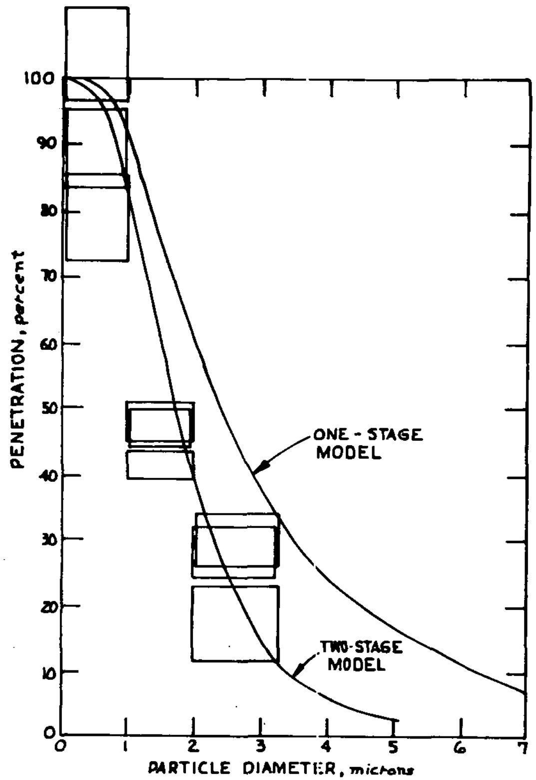

FIGURE 3

PARTICLE COLLECTION EFFICIENCY
VS IMPACTION PARAMETER
FOR IMPINGEMENT OF JETS ON
LIQUID OR SOLID SURFACES

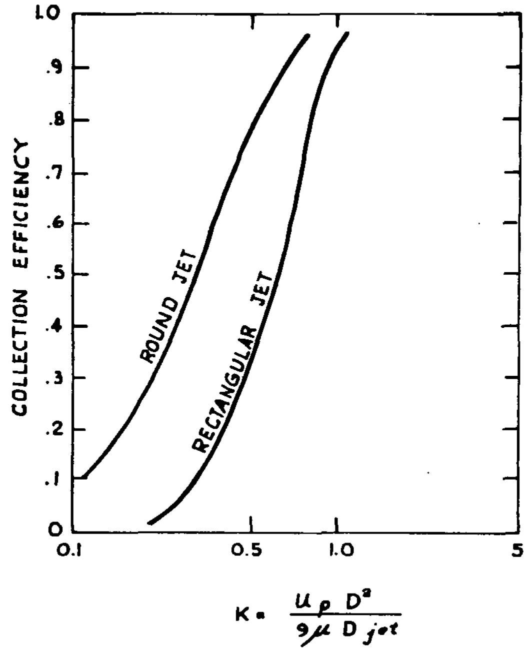

FIGURE 4

function indicated by the lower curve is just the square of the penetration calculated from Equation 6. The observed gross penetration of the test dust through the wetted screen was 54%, and the gross penetration calculated from the two-stage penetration function and Equation 3 was 56%. The same two-stage penetration function applied to the estimated size distribution for respirable dust using Equation 3 gave a gross penetration of 35%.

Jet Impingement

Some dust collection devices are based on impingement of a jet of the gas stream on a solid or liquid surface, a mechanism quite similar to impaction on targets. In this case, however, the space through which the gas stream must pass is much smaller, and the gas flow characteristics are thus different from the case where the flow is around relatively isolated bodies. The common examples of the impingement mechanism are sieve tray and ballast tray scrubbers. When the gas jet impinges on a surface, the inertia of the particles prevents them from following the sharp change of direction taken by the gas. Again, the collection efficiency is affected mainly by the variables included in K, the inertial impaction parameter. Past experimental data are correlated in Figure 4, which gives the penetration function indirectly by showing the efficiency as a function of K, for impingement of round and rectangular jets on surfaces.

The collection device tested to represent the jet impingement mechanism was an impingement scrubber consisting of a cylindrical tower containing water spray nozzles and baffle plates. The test results are shown in Figure 5. The penetration function curve shown was calculated by assuming the collection mechanism was two stages of impingement of round air jets on flat plates, with each stage having a penetration function obtained from Figure 4. Using this penetration function with Equation 3 and the estimated size distribution, a gross penetration of 27% was predicted for respirable dust through this device.

IMPINGEMENT SCRUBBER

PENETRATION AS FUNCTION OF PARTICLE DIAMETER

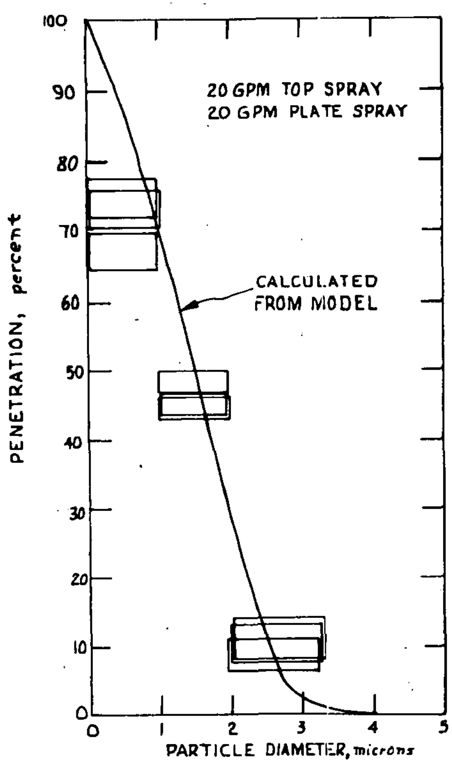

FIGURE 5

VENTURI SCRUBBER

PENETRATION AS FUNCTION OF PARTICLE DIAMETER

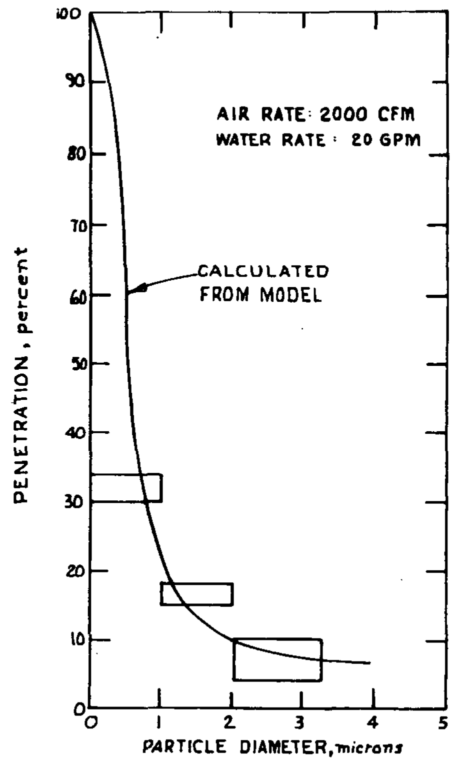

FIGURE 6

Venturi

In venturi devices, the gas stream is forced through an orifice or a narrow throat. A scrubbing liquid is introduced at or upstream of the throat, and is atomized at the throat due to the high gas velocity. The dust particles are collected by impaction on the atomized droplets. The penetration function for the venturi mechanism is given (9) as

$$P(D_p) = \exp\ [-2 \times 10^{-5}(1 - P_s)(13{,}500\ L + 1.2\ UL^{2.5}] \quad 7)$$

for the air-water system at room temperature and atmospheric pressure. P_s is the penetration calculated from Equation 6 for impaction on spheres. The spheres which are the impaction targets are the droplets atomized in the venturi throat. Their diameter (for calculating the inertial impaction parameter K) is estimated from the Nukiyama-Tanasawa correlation, which can be written as

$$D_t = \frac{16500}{U} + 1.45\ L^{1.5} \quad 8)$$

for air and water at room temperature and atmospheric pressure. Equation 8 is applicable when the air velocity is greater than 200 ft/sec.

In the experimental program, a simple venturi collector was tested, as well as two commercial devices operating primarily by the venturi mechanism. Partial test results for the simple venturi are shown in Figure 6. The observed gross penetration of the test dust was 19%, and the gross penetration calculated by using the penetration function given by Equations 7 and 8, in Equation 3 was 19%. The same penetration function applied to the estimated respirable dust size distribution gave a gross penetration of 6%. The test results for the two commercial venturi scrubbers also confirmed the venturi mechanism model.

DISCUSSION

A major conclusion from the contract program was that currently available knowledge of dust collection mechanisms is adequate both to explain the performance of a wide variety of dust collection devices and to provide a basis for the design of dust collection systems.

Potential dust collection mechanisms cannot fairly be evaluated only on the basis of the test results reported, because the tests on the various collectors were not always run at comparable conditions. Indeed, little in the way of useful conclusions could have been achieved if the program had been confined to testing various devices, even if the testing had been more extensive. But the purpose of the tests was to confirm the available models, and based on the application of those models, some general conclusions can be offered about the applicability of the different collection mechanisms to the coal mine dust problem.

1. A dry centrifugal collector cannot perform adequately for this application.

2. None of the "wet dynamic" mechanisms -- curved passages, impaction targets, jet impingement -- could meet current standards based on the respirable dust loading (10 mg/m^3) assumed in this work. However, if the respirable dust loading could be lowered, for instance by redesigning the air system in the mine entry, these mechanisms would be worth reconsidering, particularly in view of their relatively low energy and water requirements and potentially small size of the collection device.

3. The required collection efficiency could be achieved with a high energy scrubber using a venturi mechanism. The disadvantages of such a device are high pressure drop (i.e. high energy requirement) and a large water requirement. Also, there is at present no commercially available high energy scrubber which could fit in a coal mine entry.

NOMENCLATURE

(Any consistent units may be used, except in cases noted.)

D_{hub}	diameter of cyclone hub
D_p	particle diameter
D_{shell}	inside diameter of cyclone
D_t	target size: sphere - diameter (microns in Equation 8) cylinder - diameter round jet - diameter rectangular jet - width packing - nominal size
f	size distribution frequency
K	$\equiv \dfrac{\rho U D_p^2}{9 \mu D_t}$, inertial impaction parameter
L	liquid rate, gallons/thousand cubic feet of air
P	penetration
U	air velocity (ft/sec in Equations 7 and 8)
Z	packed height
μ	gas viscosity
ρ	particle density

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